An Alternative Magnetic Field
Based on Ampère's Force Law

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1 Problem

Show that Ampère's force law for two circuits with steady currents could be associated with a magnetic field.

1.1 Historical Background

In 1820-1822, Ampère examined the force between two circuits, carrying steady currents I_1 and I_2, and inferred that this could be written (here in vector notation, which Ampère did not use) as (pp. 21-24 of [4]),[2]

$$\mathbf{F}_{\text{on }1} = \oint_1 \oint_2 d^2\mathbf{F}_{\text{on }1}, \qquad d^2\mathbf{F}_{\text{on }1} = \frac{\mu_0}{4\pi} I_1 I_2 [3(\hat{\mathbf{r}} \cdot d\mathbf{l}_1)(\hat{\mathbf{r}} \cdot d\mathbf{l}_2) - 2\, d\mathbf{l}_1 \cdot d\mathbf{l}_2] \frac{\hat{\mathbf{r}}}{r^2} = -d^2\mathbf{F}_{\text{on }2}, \quad (1)$$

where $\mathbf{r} = \mathbf{l}_1 - \mathbf{l}_2$ is the distance from a current element $I_2\, d\mathbf{l}_2$ at $\mathbf{r}_2 = \mathbf{l}_2$ to element $I_1\, d\mathbf{l}_1$ at $\mathbf{r}_1 = \mathbf{l}_1$.[3,4] The integrand $d^2\mathbf{F}_{\text{on }1}$ of eq. (1) has the appeal that it changes sign if elements 1

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[2]A historical survey of the development of electrodynamics in the 1800's by one of the authors is the Appendix to [48]. A thoughtful online site about Ampère is
http://www.ampere.cnrs.fr/parcourspedagogique/index-en.php.

[3]Ampère sometimes used the notation that the angles between $d\mathbf{l}_i$ and $\mathbf{r}$ are θ_i, and the angle between the plane of $d\mathbf{l}_1$ and $\mathbf{r}$ and that of $d\mathbf{l}_2$ and $\mathbf{r}$ is ω. Then, $d\mathbf{l}_1 \cdot d\mathbf{l}_2 = dl_1\, dl_2(\sin\theta_1 \sin\theta_2 \cos\omega + \cos\theta_1 \cos\theta_2)$, and the force element of eq. (1) can be written as,

$$d^2\mathbf{F}_{\text{on }1} = \frac{\mu_0}{4\pi} I_1 I_2\, dl_1\, dl_2 (\cos\theta_1 \cos\theta_2 - 2\sin\theta_1 \sin\theta_2 \cos\omega) \frac{\hat{\mathbf{r}}}{r^2} = -d^2\mathbf{F}_{\text{on }2}. \quad (2)$$

[4]Ampère also noted the equivalents to,

$$d\mathbf{l}_1 = \frac{\partial \mathbf{r}}{\partial l_1}\, dl_1, \qquad \mathbf{r} \cdot d\mathbf{l}_1 = \mathbf{r} \cdot \frac{\partial \mathbf{r}}{\partial l_1}\, dl_1 = \frac{1}{2}\frac{\partial r^2}{\partial l_1}\, dl_1 = r\frac{\partial r}{\partial l_1}\, dl_1, \qquad d\mathbf{l}_2 = -\frac{\partial \mathbf{r}}{\partial l_2}\, dl_2, \qquad \mathbf{r} \cdot d\mathbf{l}_2 = -r\frac{\partial r}{\partial l_2}\, dl_2, \quad (3)$$

where l_1 and l_2 measure distance along the corresponding circuits in the directions of their currents. Then,

$$d\mathbf{l}_1 \cdot d\mathbf{l}_2 = -d\mathbf{l}_1 \cdot \frac{\partial \mathbf{r}}{\partial l_2}\, dl_2 = -\frac{\partial}{\partial l_2}(\mathbf{r} \cdot d\mathbf{l}_1)\, dl_2 = -\frac{\partial}{\partial l_2}\left(r\frac{\partial r}{\partial l_1}\right) dl_1\, dl_2 = -\left(\frac{\partial r}{\partial l_1}\frac{\partial r}{\partial l_2} + r\frac{\partial^2 r}{\partial l_1 \partial l_2}\right) dl_1\, dl_2, \quad (4)$$

and eq. (1) can also be written in forms closer to those used by Ampère,

$$d^2\mathbf{F}_{\text{on }1} = \frac{\mu_0}{4\pi} I_1 I_2\, dl_1\, dl_2 \left[2r\frac{\partial^2 r}{\partial l_1 \partial l_2} - \frac{\partial r}{\partial l_1}\frac{\partial r}{\partial l_2}\right] \frac{\hat{\mathbf{r}}}{r^2} = \frac{\mu_0}{4\pi} 2 I_1 I_2\, dl_1\, dl_2 \frac{\partial^2 \sqrt{r}}{\partial l_1 \partial l_2}\frac{\hat{\mathbf{r}}}{\sqrt{r}} = -d^2\mathbf{F}_{\text{on }2}. \quad (5)$$

and 2 are interchanged, and so suggests a force law for current elements that obeys Newton's third law.[5]

In 1825, Ampère noted, p. 214 of [7], p. 29 of [4], p. 366 of the English translation in [46], that for a closed circuit, eq. (1) can be rewritten as,[6]

$$\mathbf{F}_{\rm on\ 1} = \frac{\mu_0}{4\pi} I_1 I_2 \oint_1 \oint_2 \frac{(d\mathbf{l}_1 \cdot \hat{\mathbf{r}})\, d\mathbf{l}_2 - (d\mathbf{l}_1 \cdot d\mathbf{l}_2)\, \hat{\mathbf{r}}}{r^2} = \oint_1 I_1 d\mathbf{l}_1 \times \frac{\mu_0}{4\pi} \oint_2 \frac{I_2\, d\mathbf{l}_2 \times \hat{\mathbf{r}}}{r^2}\,, \qquad (7)$$

in vector notation (which, of course, he did not use).[7] Ampère made very little comment on this result.[8] However, in retrospect, we see that the form (7) lends itself to the interpretation that the force between closed circuits with steady currents can be written in terms of a magnetic field $\mathbf{B}_{\rm B-S}$ as,

$$\mathbf{F}_{\rm B-S} = \oint I\, d\mathbf{l} \times \mathbf{B}, \qquad (8)$$

$$\mathbf{B}_{\rm B-S} = \frac{\mu_0}{4\pi} \oint \frac{I\, d\mathbf{l} \times \hat{\mathbf{r}}}{r^2}\,, \qquad (9)$$

both equations of which are often called the Biot-Savart law.[9,10]

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[5]Maxwell called Ampère the "Newton of electricity" in Art. 528 of [28].

[6]Note that for a fixed point 2, $d\mathbf{l}_1 = d\mathbf{r}$, and $dr = d\mathbf{r} \cdot \hat{\mathbf{r}} = d\mathbf{l}_1 \cdot \hat{\mathbf{r}}$. Then, for any function $f(r)$, $df = (df/dr)\, dr = (df/dr)\, d\mathbf{l}_1 \cdot \hat{\mathbf{r}}$. In particular, for $f = -1/r$, $df = d\mathbf{l}_1 \cdot \hat{\mathbf{r}}/r^2$, so the first term of the first form of eq. (6) is a perfect differential with respect to $\mathbf{l}_1$. Hence, when integrating around a closed loop 1, the first term does not contribute, and it is sufficient to write (as first argued by Neumann, p. 67 of [12]),

$$\mathbf{F}_{\rm on\ 1} = -\frac{\mu_0}{4\pi} I_1 I_2 \oint_1 \oint_2 \frac{d\mathbf{l}_1 \cdot d\mathbf{l}_2}{r^2}\, \hat{\mathbf{r}} = -\mathbf{F}_{\rm on\ 2}. \qquad (6)$$

[7]Ampère's force law for closed circuits with steady currents can be written in many other ways as well. Maxwell gave an early survey of this in Arts. 510-526 of [28]. Surprisingly, Maxwell preferred Ampère's force law (his eq. (42) of Art. 526) to that of Biot and Savart (which he identified with Grassmann, eq. (43) of Art. 526), stating that Ampère's form "is undoubtedly the best". Apparently, Maxwell did not realize that his vector-diffential equations for the magnetic field lead most directly to the Biot-Savart-Grassmann form. A review by one of the authors is in [45].

[8]As a consequence, the form (7) is generally attributed to Grassmann [11], as in [43], for example.

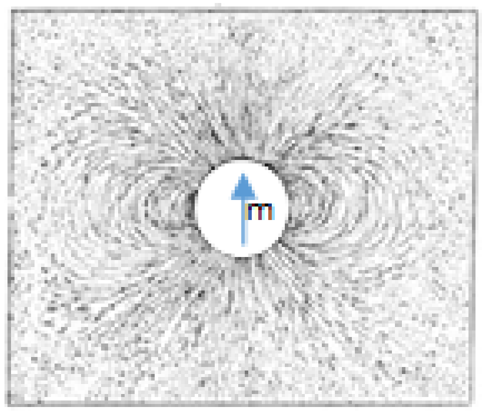
[9]Biot and Savart [1, 2] actually studied on the force due to an electric current I in a wire on one pole, p, of a long, thin magnet. Their initial interpretation of the results was somewhat incorrect, which was remedied by Biot in 1821 and 1824 [3, 6] with a form that can be written in vector notation (and in SI units) as,

$$\mathbf{F} = \frac{\mu_0\, p}{4\pi} \oint \frac{I\, d\mathbf{l} \times \hat{\mathbf{r}}}{r^2}\,, \qquad (10)$$

where $\mathbf{r}$ is the distance from a current element $I\, d\mathbf{l}$ to the magnetic pole. There was no immediate interpretation of eq. (10) in terms of a magnetic field, $\mathbf{B} = \mathbf{F}/p$.

[10]Equations (8)-(9) are a factorization of the Biot-Savart force law (7), and both equations are called the Biot-Savart law in, for example, sec. 7-6, p. 125 of [32]. The earliest description of eq. (8) as the Biot-Savart law may be in sec. 2 of [30]. However, many authors call only the eq. (9) the Biot-Savart law (but it is called Laplace's law in France); an early example is on p. 220 of [29]. Equation (8) is often called the Lorentz force law, although it was first stated by Maxwell, somewhat obscurely, as the third term in eqs. (12)-(14), p. 172 of [23], and more clearly in eq. (11), Art. 603 of [28].

Ampère had no concept of a magnetic field, which originated with Faraday, inspired in part by patterns of iron filings on a sheet near a magnet.[11] Of particular interest here is Fig. 3 from Art. 3295 of [18], in which Faraday showed the pattern of iron filings in a plane containing the axis of a small dipole magnet, as shown below.



This pattern corresponds to the lines of force of a magnetic dipole $\mathbf{m}$ on a hypothetical magnetic pole p as deduced by Poisson, eq. (9), p. 507 of [5] (1824),

$$\mathbf{F} = -p\,\boldsymbol{\nabla}\frac{\mathbf{m}\cdot\hat{\mathbf{r}}}{r^2} = p\frac{3(\mathbf{m}\cdot\hat{\mathbf{r}})\,\hat{\mathbf{r}} - \mathbf{m}}{r^3}\,. \tag{11}$$

where $\mathbf{r}$ is the vector from the center of the dipole $\mathbf{m}$ to the pole p. This was regarded by Poisson as an action-at-a-distance force, and he did not consider the possibility of a magnetic force field such as $\mathbf{B} = \mathbf{F}/p$ that existed in vacuum at points unoccupied by magnetic poles.

Our present view is that iron filings are not magnetic poles, but magnetic dipoles, which align themselves along lines of the magnetic field $\mathbf{B}$.

The first to adopt Faraday's concept of a magnetic field was Thomson (later Lord Kelvin), who discussed the magnetic field of a magnetic dipole $\mathbf{m}$ in sec. II of [15] (1846). However, he did not follow the path of Poisson (to write $\mathbf{B} = -\boldsymbol{\nabla}(\mathbf{m}\cdot\hat{\mathbf{r}}/r^2)$, but simply stated that,

$$\mathbf{B} = \boldsymbol{\nabla}\times\mathbf{A}, \qquad \text{where} \qquad \mathbf{A} = \frac{\mathbf{m}\times\mathbf{r}}{r^3}\,, \tag{12}$$

in his eq. (II) where $\mathbf{B} = (X, Y, Z)$ and his eq. (3) where $\mathbf{A} = (\alpha, \beta, \gamma)$. This is the first

[11] Faraday first mentioned *magnetic lines of force* in Art. 114 of [8] (1831): *By magnetic curves, I mean the lines of magnetic forces, however modified by the juxtaposition of poles, which would be depicted by iron filings; or those to which a very small magnetic needle would form a tangent.*

In 1845, Art. 2247 of [13], the term *magnetic field* appears for the first time in print: *The ends of these bars form the opposite poles of contrary name; the magnetic field between them can be made of greater or smaller extent, and the intensity of the lines of magnetic force be proportionately varied.*

In 1852, Faraday published a set of speculative comments [18] in the Phil. Mag. (rather than Phil. Trans. Roy. Soc. London, the usual venue for his *Experimental Researches*), arguing more strongly for the physical reality of the lines of force.

In Art. 3258 he considered the effect of a magnet in vacuum, concluding (perhaps for the first time) that the lines of force have existence independent of a material medium:
A magnet placed in the middle of the best vacuum we can produce...acts as well upon a needle as if it were surrounded by air, water or glass; and therefore these lines exist in such a vacuum as well as where there is matter.

appearance of a vector potential in print.[12] Like Poisson, Thomson provided no figure, but gave a brief verbal description that suggests he was aware of our form (11), given by Poisson, which agrees with our eq. (12), assuming that $\mathbf{F} = p\mathbf{B}$.

Meanwhile, in 1845, Neumann followed the examples of Lagrange, Laplace and Poisson in relating forces of gravity and electrostatics to (scalar) potentials, and sought a potential for Ampère's force law (1) between two (closed) current loops. For this, he noted that Ampère's force law can be rewritten in the form (6), which permits us to write $\mathbf{F}_{\rm on1} = -\boldsymbol{\nabla} U$ where, U is the scalar potential (energy) given on p. 67 of [12],[13]

$$U = \frac{\mu_0}{4\pi} I_1 I_2 \oint_1 \oint_2 \frac{d\mathbf{l}_1 \cdot d\mathbf{l}_2}{r} \qquad (14)$$

in SI units. We now also write this as,

$$U = I_i \oint_i d\mathbf{l}_i \cdot \mathbf{A}_j = I_i \int d\mathbf{Area}_i \cdot \boldsymbol{\nabla} \times \mathbf{A}_j = I_i \int d\mathbf{Area}_i \cdot \mathbf{B}_j = I_i \Phi_{ij}, \qquad (15)$$

where Φ_{ij} is the magnetic flux through circuit i due to the current I_j in circuit j, and,

$$\mathbf{A}_j = \frac{\mu_0}{4\pi} \oint_j \frac{I_j \, d\mathbf{l}_j}{r}\,, \qquad (16)$$

such that Neumann is often credited for inventing the vector potential $\mathbf{A}$, although he appears not to have written his eq. (14) in any of the forms of eq. (15).

In 1870, Helmholtz made a review of electrodynamics, and in eq. (1), p. 76 of [27],[14] he stated that a general form for the magnetic interaction energy (his P, but our U) of two

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[12] In 1867 Gauss posthumously published an analysis that he dated to 1835 (p. 609 of [26]), in which he stated that a time-dependent electric current leads to an electric field which is the time derivative of what we now called the vector potential. English translation from [38]:

The Law of Induction
Found out Jan. 23, 1835, at 7 a.m. before getting up.

> 1. The electricity producing power, which is caused in a point P by a current-element $\boldsymbol{\gamma}$, at a distance from P, $= r$, is during the time dt the difference in the values of $\boldsymbol{\gamma}/r$ corresponding to the moments t and dt, divided by dt. where $\boldsymbol{\gamma}$ is considered both with respect to size and direction. This can be expressed briefly and clearly by
>
> $$-\frac{\mathrm{d}(\boldsymbol{\gamma}/r)}{\mathrm{d}t}\,. \qquad (13)$$

Gauss' unpublished insight that electromagnetic induction is related to the negative time derivative of a scalar quantity was probably communicated in the late 1830's to his German colleagues, of whom Weber was the closest.

On p. 612 (presumably also from 1835), Gauss noted a relation (here transcribed into vector notation) between the vector $\mathbf{A} = \oint d\mathbf{l}/r$ and the magnetic scalar potential Ω of a circuit with unit electrical current (which he related to the solid angle subtended by the circuit on p. 611), $-\boldsymbol{\nabla}\Omega = \boldsymbol{\nabla} \times \mathbf{A}$. While we would identify $-\boldsymbol{\nabla}\Omega$ with the magnetic field $\mathbf{H}$, Gauss called it the "electricity-generating force". In any case, this is the earliest (claimed) appearance of the curl operator (although published later than MacCullagh's use of it, p. 22 of [10] (1839)).

[13] If we write eq. (14) as $U = I_1 I_2 M_{12}$, then M_{12} is the mutual inductance of circuits 1 and 2.

[14] For comments by one of the authors on this paper, see [47]. See also commentaries in [35, 39, 40, 41].

current elements, which are part of closed circuits of steady currents, could be written as a combination of the forms he attributed to Neumann [12, 16] and to Weber [14, 17],[15]

$$d^2U = \frac{\mu_0}{4\pi}\left(\frac{1+k}{2}\frac{I_1\,d\mathbf{l}_1 \cdot I_2\,d\mathbf{l}_2)}{r} + \frac{1-k}{2}\frac{(I_1\,d\mathbf{l}_1 \cdot \hat{\mathbf{r}})(I_2\,d\mathbf{l}_2 \cdot \hat{\mathbf{r}})}{r}\right), \tag{17}$$

where $k = 1$ for Neumann's form and $k = -1$ for Weber's. Then, in eq. (1^a) he noted that the scalar U is related to a vector potential (his (U, V, W) but our $\mathbf{A}$) as $U = \int \mathbf{J}\cdot\mathbf{A}\,d\mathrm{Vol}/2$, noting that $I\,d\mathbf{l} \leftrightarrow \mathbf{J}\,d\mathrm{Vol}$ where $\mathbf{J}$ is the (steady) current density (which obeys $\boldsymbol{\nabla}\cdot\mathbf{J} = 0$),[16]

$$\mathbf{A} = \frac{1+k}{2}\frac{\mu_0}{4\pi}\int \frac{\mathbf{J}}{r}\,d\mathrm{Vol} + \frac{1-k}{2}\frac{\mu_0}{4\pi}\int \frac{(\mathbf{J}\cdot\hat{\mathbf{r}})\,\hat{\mathbf{r}}}{r}\,d\mathrm{Vol} \equiv \frac{1+k}{2}\mathbf{A}_\mathrm{N} + \frac{1-k}{2}\mathbf{A}_\mathrm{W}, \tag{18}$$

$$\mathbf{A}_\mathrm{N} = \frac{\mu_0}{4\pi}\int \frac{\mathbf{J}}{r}\,d\mathrm{Vol}, \tag{19}$$

$$\mathbf{A}_\mathrm{W} = \frac{\mu_0}{4\pi}\int \frac{(\mathbf{J}\cdot\hat{\mathbf{r}})\,\hat{\mathbf{r}}}{r}\,d\mathrm{Vol}, \tag{20}$$

where $\mathbf{r} = \mathbf{x} - \mathbf{x}'$. However, Neumann never wrote the form called $\mathbf{A}_\mathrm{N}$ here. Kirchhoff, p. 530 of [21], attributed $\mathbf{A}_\mathrm{W}$ to Weber, who later transcribed Kirchhoff's paper into sec. I.1. of [25], with $\mathbf{A}_\mathrm{W}$ appearing on p. 578.[17,18]

1.2 The Problem

Consider the magnetic field,

$$\mathbf{B}_{\mathrm{A-W}}(\mathbf{x}) = \frac{\mu_0}{4\pi}\oint I\,d\mathbf{l}\cdot\hat{\mathbf{r}}\frac{\hat{\mathbf{r}}}{r^2} = \frac{\mu_0}{4\pi}\int \mathbf{J}(\mathbf{x}')\cdot\hat{\mathbf{r}}\frac{\hat{\mathbf{r}}}{r^2}\,d\mathrm{Vol} \qquad (\mathbf{r} = \mathbf{x} - \mathbf{x}'), \tag{21}$$

which has the form of $\mathbf{A}_\mathrm{W}$ of eq. (20), but with the factor r in the denominator replaced by r^2.[19]

Show that the Ampère force law (1) for $d^2\mathbf{F}_{\mathrm{on}\ 1} = d^2\mathbf{F}_\mathrm{A}(\mathbf{x}, \mathbf{x}')$ on current element $I_1\,d\mathbf{l}_1$ at $\mathbf{x}$ due to element $I_2\,d\mathbf{l}_2$ at $\mathbf{x}'$ can be related to this magnetic field by,

$$d\mathbf{B}_{\mathrm{A-W}}(\mathbf{x}, \mathbf{x}') = \frac{\mu_0}{4\pi}I_2\,d\mathbf{l}_2\cdot\hat{\mathbf{r}}\frac{\hat{\mathbf{r}}}{r^2} = \frac{\mu_0}{4\pi}I_2\,d\mathbf{l}_2\cdot\mathbf{r}\frac{\mathbf{r}}{r^4}, \tag{22}$$

$$d^2\mathbf{F}_\mathrm{A}(\mathbf{x}, \mathbf{x}') = -I_1\,d\mathbf{l}_1\cdot\{d\mathbf{B}_{\mathrm{A-W}}(\mathbf{x}, \mathbf{x}') + 2\boldsymbol{\nabla}([\mathbf{B}_{\mathrm{A-W}}(\mathbf{x}, \mathbf{x}')\cdot\mathbf{r}]\}\,\hat{\mathbf{r}}, \tag{23}$$

[15]See also sec. IIB of [43], and [45]. The energy that Helmholtz associated with Weber was never actually advocated by the latter, who had a different vision of magnetic energy, as discussed in sec. A.23 of [48].

[16]Thus, we cannot write for an isolated current element that $d\mathbf{A} = \mu_0 I[(1+k)d\mathbf{l} + (1-k)(d\mathbf{l}\cdot\hat{\mathbf{r}})\,\hat{\mathbf{r}}]/8\pi r$.

[17]Both $\mathbf{A}_\mathrm{N}$ and $\mathbf{A}_\mathrm{W}$ lead to the same magnetic field, $\mathbf{B} = \boldsymbol{\nabla}\times\mathbf{A}_\mathrm{N} = \boldsymbol{\nabla}\times\mathbf{A}_\mathrm{W}$, which is an early example of gauge invariance.

[18]Helmholtz' discussion was tacitly restricted to electro- and magnetostatics, such that his eq. (3^a), p. 80, that $\boldsymbol{\nabla}\cdot\mathbf{A} = k\,dV/dt$, where V is the instantaneous electric scalar potential, led him to identify $k = 0$ with Maxwell's theory [24], which emphasized $\boldsymbol{\nabla}\cdot\mathbf{A} = 0$, although we would now consider $k = 1$ to be compatible with Maxwell's theory for static electromagnetism. Maxwell was more interested in electrodynamics than electro/magnetostatics, such that his only mention of the "Neumann" magnetostatic scalar potential, our eq. (14), was in eq. (9), Art. 422 of [28].

[19]The field $\mathbf{B}_{\mathrm{A-W}}$ is a vector, while the usual magnetic field $\mathbf{B}$ (as in eq. (9)) is a pseudovector.

where $\mathbf{r}$ is the distance vector from $\mathbf{l}_1$ to $\mathbf{l}_2$ introduced in eq. (1). Show also that $\boldsymbol{\nabla}\cdot\mathbf{B}_{\rm A-W} = 0$, consistent with Ampère's view that magnetism is due to electric currents rather than magnetic charges/poles.

Compute the magnetic field (21) due to a magnetic dipole $\mathbf{m}$, a small current loop of radius a, current I, with $\mathbf{m}$ along the axis of the loop, and $m = \pi a^2 I$. Compare the field lines for this model of a magnetic dipole with the figure from Faraday on p. 3 above.

Would Faraday have accepted the field $\mathbf{B}_{\rm A-W}$ as a valid physical description of the magnetic field?

2 Solution

From eq. (22), we have,

$$\begin{aligned}\boldsymbol{\nabla}[d\mathbf{B}_{\rm A-W}(\mathbf{x},\mathbf{x}')\cdot\mathbf{r}] &= \frac{\mu_0}{4\pi}I_2\boldsymbol{\nabla}\left(\frac{d\mathbf{l}_2\cdot\mathbf{r}}{r^2}\right) = \frac{\mu_0}{4\pi}I_2\left(-\frac{2d\mathbf{l}_2\cdot\mathbf{r}}{r^3}\boldsymbol{\nabla}r + \frac{\boldsymbol{\nabla}(d\mathbf{l}_2\cdot\mathbf{r})}{r^2}\right) \\ &= \frac{\mu_0}{4\pi}I_2\left(-\frac{2d\mathbf{l}_2\cdot\mathbf{r}}{r^4}\mathbf{r} + \frac{d\mathbf{l}_2}{r^2}\right) = \frac{\mu_0}{4\pi}I_2\left(-\frac{2d\mathbf{l}_2\cdot\hat{\mathbf{r}}}{r^2}\hat{\mathbf{r}} + \frac{d\mathbf{l}_2}{r^2}\right).\end{aligned} \tag{24}$$

Then,

$$\begin{aligned}&-I_1\,d\mathbf{l_1}\cdot[d\mathbf{B}_{\rm A-W}(\mathbf{x},\mathbf{x}') + 2\boldsymbol{\nabla}(d\mathbf{B}_{\rm A-W}(\mathbf{x},\mathbf{x}')\cdot\mathbf{r})]\,\hat{\mathbf{r}} \\ &= -\frac{\mu_0}{4\pi}I_1\,d\mathbf{l}_1\cdot\left[I_2(d\mathbf{l}_2\cdot\hat{\mathbf{r}})\frac{\hat{\mathbf{r}}}{r^2} + 2I_2\left(-\frac{2d\mathbf{l}_2\cdot\hat{\mathbf{r}}}{r^2}\hat{\mathbf{r}} + \frac{d\mathbf{l}_2}{r^2}\right)\right]\hat{\mathbf{r}} \\ &= \frac{\mu_0}{4\pi}I_1\,d\mathbf{l}_1\cdot\left(3I_2(d\mathbf{l}_2\cdot\hat{\mathbf{r}})\frac{\hat{\mathbf{r}}}{r^2} - \frac{2I_2\,d\mathbf{l}_2}{r^2}\right)\hat{\mathbf{r}} = \frac{\mu_0}{4\pi}I_1 I_2\,[3(d\mathbf{l}_1\cdot\hat{\mathbf{r}})(d\mathbf{l}_2\cdot\hat{\mathbf{r}}) - 2\,d\mathbf{l}_1\cdot d\mathbf{l}_2]\,\frac{\hat{\mathbf{r}}}{r^2} \\ &= d^2\mathbf{F}_{\rm A}(\mathbf{x},\mathbf{x}') = d^2\mathbf{F}_{\rm on\ 1},\end{aligned} \tag{25}$$

according to Ampère's form (1).

Thus, Ampère's force law (1) can be related to a magnetic field $\mathbf{B}_{\rm A-W}$ if we allow the force law (22) to depend on the spatial derivatives of $\mathbf{B}_{\rm A-W}$ as well as $\mathbf{B}_{\rm A-W}$ itself. Such a derivative coupling is not favored in the simplest implementation of a field theory, but cannot be excluded altogether. However, the force (22) on current element $I_1\,d\mathbf{l}_1$ is not a function only of this element and the field $\mathbf{B}_{\rm A-W}$ at the element, so it not in the spirit of Faraday's vision of a field theory.

2.1 $\boldsymbol{\nabla}\cdot\mathbf{B}_{\rm A-W} = 0$

The divergence of $\mathbf{B}_{\rm A-W}(\mathbf{x})$ is, noting that $\boldsymbol{\nabla}$ acts on $\mathbf{r} = \mathbf{x} - \mathbf{x}'$ but not on $\mathbf{J}(\mathbf{x}')$,

$$\begin{aligned}\boldsymbol{\nabla}\cdot\mathbf{B}_{\rm A-W}(\mathbf{x}) &= \frac{\mu_0}{4\pi}\int\boldsymbol{\nabla}\cdot\left(\frac{\mathbf{J}(\mathbf{x}')\cdot\mathbf{r}}{r^4}\mathbf{r}\right)\,d{\rm Vol}' \\ &= \frac{\mu_0}{4\pi}\int\left[\frac{\mathbf{J}(\mathbf{x}')\cdot\mathbf{r}}{r^4}\boldsymbol{\nabla}\cdot\mathbf{r} + \mathbf{r}\cdot\boldsymbol{\nabla}\left(\frac{\mathbf{J}(\mathbf{x}')\cdot\mathbf{r}}{r^4}\right)\right]\,d{\rm Vol}' \\ &= \frac{\mu_0}{4\pi}\int\left[\frac{3\mathbf{J}(\mathbf{x}')\cdot\mathbf{r}}{r^4} + \mathbf{r}\cdot\left(\frac{\boldsymbol{\nabla}(\mathbf{J}(\mathbf{x}')\cdot\mathbf{r})}{r^4} - \frac{4(\mathbf{J}(\mathbf{x}')\cdot\mathbf{r})}{r^5}\boldsymbol{\nabla}r\right)\right]\,d{\rm Vol}'\end{aligned}$$

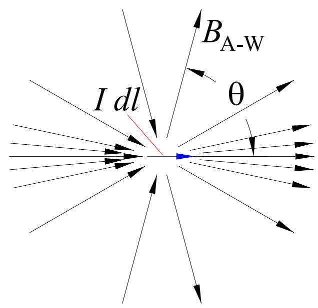
$$= \frac{\mu_0}{4\pi} \int \left[\frac{3\mathbf{J}(\mathbf{x}') \cdot \mathbf{r}}{r^4} + \mathbf{r} \cdot \left(\frac{\mathbf{J}(\mathbf{x}')}{r^4} - \frac{4(\mathbf{J}(\mathbf{x}') \cdot \mathbf{r})\mathbf{r}}{r^6} \right) \right] d\text{Vol}' = 0, \qquad (26)$$

away from $r = 0$, *i.e.*, for source currents away from the observation point.

To ascertain the behavior of $\mathbf{B}_{\text{A-W}}$ for small r, it is useful to consider its flux across the surface of a sphere of radius r, within which the current $\mathbf{J}$ is approximately constant.

$$\Phi = \int (\mathbf{B}_{\text{A-W}} \cdot \hat{\mathbf{r}})\, d\text{Area} = \frac{\mu_0}{4\pi} \int_{-1}^{1} \frac{\mathbf{J} \cdot \hat{\mathbf{r}}}{r^2}\, 2\pi r^2\, d\cos\theta = \frac{\mu_0 J}{2} \int_{-1}^{1} \cos\theta\, d\cos\theta = 0, \qquad (27)$$

taking the z-axis to be along the direction of $\mathbf{J}$ at the center of the sphere. That is, the magnetic field (21) for a current element $\mathbf{J}\, d\text{Vol} = I\, d\mathbf{l}$ has lines of $\mathbf{B}_{\text{A-W}}$ diverging from the current element in one hemisphere, and converging on it in the other, such that the total flux into/out of the current element is zero. Then, together with eq. (26), we see that $\nabla \cdot \mathbf{B}_{\text{A-W}} = 0$ everywhere.



Hence, there exists a vector potential $\mathbf{A}_{\text{A-W}}$ such that $\mathbf{B}_{\text{A-W}} = \nabla \times \mathbf{A}_{\text{A-W}}$. A particular form of the vector potential is,[20]

$$\mathbf{A}_{\text{A-W}}(\mathbf{x}) = \frac{\mu_0}{4\pi} \int \frac{\mathbf{J}(\mathbf{x}') \times \mathbf{r}}{2r^2}\, d\text{Vol}'. \qquad (29)$$

2.2 $\nabla \times \mathbf{B}_{\text{A-W}}$ (Nov. 2, 2022)

As first noted by Helmholtz, Theorem VI, p. 61 of [22] (1858), to specify a vector field via first-order differential equations, both the curl and the divergence of the field must be known. For the usual magnetic field $\mathbf{B}$, its curl for steady-state examples is $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$, which is often called "Ampère's Law".[21]

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[20]
$$\nabla \times \left(\frac{\mathbf{J} \times \mathbf{r}}{r^2} \right) = \frac{\mathbf{J}}{r^2}(\nabla \cdot \mathbf{r}) - \mathbf{r} \left(\nabla \cdot \frac{\mathbf{J}}{r^2} \right) + (\mathbf{r} \cdot \nabla)\frac{\mathbf{J}}{r^2} - \left(\frac{\mathbf{J}}{r^2} \cdot \nabla \right) \mathbf{r}$$
$$= \frac{3\mathbf{J}}{r^2} - \mathbf{r} \left(\mathbf{J} \cdot \nabla \frac{1}{r^2} \right) - \frac{2\mathbf{J}}{r^3}(\mathbf{r} \cdot \nabla) r - \frac{\mathbf{J}}{r^2} = \frac{2\mathbf{J}}{r^2} + 2\mathbf{r}\frac{\mathbf{J} \cdot \mathbf{r}}{r^4} - \frac{2\mathbf{J}}{r^2} = \frac{2(\mathbf{J} \cdot \mathbf{r})\mathbf{r}}{r^4} \propto d\mathbf{B}_{\text{A-W}}. \qquad (28)$$

[21] In 1826, Ampère gave lectures that included discussion of the force on a magnetic pole due to an electric current, noting that the line integral of the tangential force around a closed loop is proporptional to the electric current that passes through the loop, independent of the shape of the loop [36, 44]. This was a statement of what is now called "Ampère's (circuital) law". While Ampère did not consider the now-usual magnetic field $\mathbf{B}$, we note that the force on a magnetic pole p is $\mathbf{F} = p\,\mathbf{B}$, so his conclusion that $\oint \mathbf{F} \cdot d\mathbf{l} \propto I$, where I is the electric current through the loop of integration, implies also that $\oint \mathbf{B} \cdot d\mathbf{l} \propto I$.

This "law" was noted by Maxwell on p. 56 of [20], who deduced from it via Stokes' theorem that $\nabla \times \mathbf{H} = \mathbf{J}$, taking note of the relation $\mathbf{B} = \mu\mathbf{H}$ for linear media, Maxwell's eq. (B), p. 53, where our μ is Maxwell's k_2.

The curl of $\mathbf{B}_{\rm A-W}$ is,

$$\nabla \times \mathbf{B}_{\rm A-W}(\mathbf{x}) = \frac{\mu_0}{4\pi} \int \nabla \times \left(\frac{\mathbf{J}(\mathbf{x}') \cdot \mathbf{r}}{r^4} \mathbf{r} \right) d\mathrm{Vol}'$$

$$= \frac{\mu_0}{4\pi} \int \left[\frac{\mathbf{J}(\mathbf{x}') \cdot \mathbf{r}}{r^4} \nabla \times \mathbf{r} - \mathbf{r} \times \nabla \left(\frac{\mathbf{J}(\mathbf{x}') \cdot \mathbf{r}}{r^4} \right) \right] d\mathrm{Vol}'$$

$$= -\frac{\mu_0}{4\pi} \int \mathbf{r} \times \left(\frac{\nabla(\mathbf{J}(\mathbf{x}') \cdot \mathbf{r})}{r^4} - \frac{4(\mathbf{J}(\mathbf{x}') \cdot \mathbf{r})}{r^5} \nabla r \right) d\mathrm{Vol}'$$

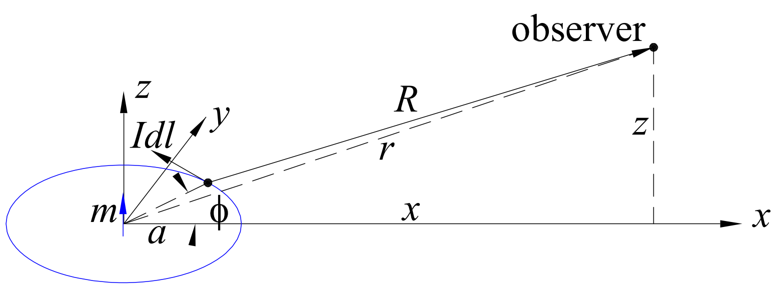
$$= -\frac{\mu_0}{4\pi} \int \mathbf{r} \times \left(\frac{\mathbf{J}(\mathbf{x}')}{r^4} - \frac{4(\mathbf{J}(\mathbf{x}') \cdot \mathbf{r})\,\mathbf{r}}{r^6} \right) d\mathrm{Vol}' = \frac{\mu_0}{4\pi} \int \frac{\mathbf{J}(\mathbf{x}') \times \mathbf{r}}{r^4} \, d\mathrm{Vol}'. \tag{30}$$

This is nonzero throughout all space, and does not lend itself to a simple interpretation as to the source of the magnetic field, as does Ampère's law, $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$, for the usual (static) magnetic field. $\mathbf{B}$.

2.3 Three Examples

2.3.1 Magnetic Dipole

We now consider a magnetic dipole $\mathbf{m} = \pi a^2 I \, \hat{\mathbf{z}}$, *i.e.*, a small, circular loop of radius a, centered on the origin, that carries steady current I.



We calculate $\mathbf{B}_{\rm A-W}$ at the point $\mathbf{r} = (x \gg a, 0, z)$, with $r = \sqrt{x^2 + z^2}$. For a current element $I\,dl = Ia\,d\phi$ located at angle ϕ to the x-axis, *i.e.*, at $\mathbf{r}' = (a\cos\phi, a\sin\phi, 0)$ in (x, y, z) coordinates, we have, with $\mathbf{R} = \mathbf{r} - \mathbf{r}'$,

$$d\mathbf{l} = a\,d\phi\,(-\sin\phi, \cos\phi, 0), \qquad \mathbf{R} = (x - a\cos\phi, -a\sin\phi, z), \qquad d\mathbf{l} \cdot \mathbf{R} = -ax\,d\phi \sin\phi, \tag{31}$$

$$R = \sqrt{x^2 - 2ax\cos\phi + a^2 + z^2} \approx \sqrt{x^2 + z^2} \left(1 - \frac{ax\cos\phi}{x^2 + z^2} \right) = r \left(1 - \frac{ax\cos\phi}{r^2} \right), \tag{32}$$

$$\mathbf{B}_{\rm A-W} = \frac{\mu_0}{4\pi} \oint I \frac{(d\mathbf{l} \cdot \mathbf{R})\mathbf{R}}{R^4}$$

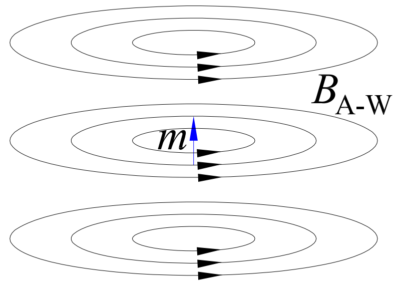
$$\approx \frac{\mu_0}{4\pi} \frac{aI}{r^4} \int_0^{2\pi} d\phi\,(-x\sin\phi) \left(1 + \frac{4ax\cos\phi}{r^2} \right) (x - a\cos\phi, -a\sin\phi, z)$$

$$= \frac{\mu_0}{4\pi} \frac{aI}{r^4} (0, \pi a x, 0) = \frac{\mu_0}{4\pi} \frac{mx}{r^4} \hat{\mathbf{y}} = \frac{\mu_0}{4\pi} \frac{mx}{r^4} \hat{\boldsymbol{\phi}} = \frac{\mu_0}{4\pi} \frac{\mathbf{m} \times \mathbf{r}}{r^4} = \nabla \times \frac{\mu_0}{4\pi} \frac{\mathbf{m}}{2r^2} = \nabla \times \mathbf{A}_{\rm A-W}. \tag{33}$$

See also [19], and Art. 498 of [28].

Objections to the identification of Ampère's circuital law of 1826 with "Ampère's law" in [37, 42] are too narrow, in the view of the present authors.

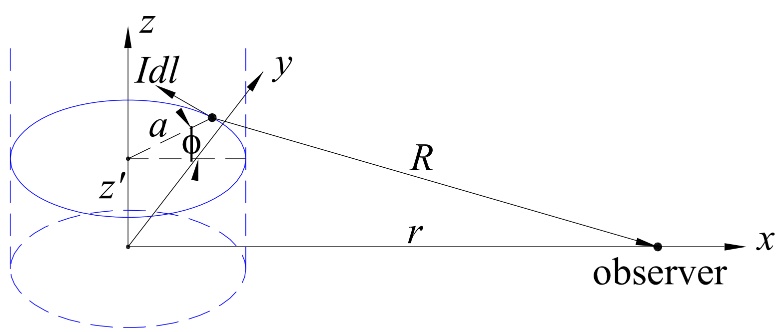
Lines of the $\mathbf{B}_{\mathrm{A-W}} \propto \mathbf{m} \times \hat{\mathbf{r}}/r^3$ are circles centered on the axis $\mathbf{m}$, and do not at all resemble the pattern of iron filings found by Faraday for a small dipole magnet (p. 3 above).



Hence, while the field $\mathbf{B}_{\mathrm{A-W}}$ is mathematically consistent with Ampère's force law (1) between two circuits with steady currents, it seems unappealing physically, and would not have been accepted by Faraday.

2.3.2 Infinite Solenoid (Aug. 20, 2021)

In this section, we consider an infinite solenoid of radius a along the z-axis, with steady, azimuthal surface current I per unit length in z.



We calculate $\mathbf{B}_{\mathrm{A-W}}$ at the point $\mathbf{r} = (r, 0, 0)$. For a current element $I\,dl = I a\,d\phi$ located at angle ϕ to the x-axis at height z', *i.e.*, at $\mathbf{r}' = (a\cos\phi, a\sin\phi, z')$, we have, with $\mathbf{R} = \mathbf{r} - \mathbf{r}'$,

$$d\mathbf{l} = a\,d\phi\,(-\sin\phi, \cos\phi, 0), \quad \mathbf{R} = (r - a\cos\phi, -a\sin\phi, -z'), \quad d\mathbf{l}\cdot\mathbf{R} = -ar\,d\phi\sin\phi, \tag{34}$$

$$R = \sqrt{r^2 - 2ar\cos\phi + a^2 + z'^2}, \tag{35}$$

$$\begin{aligned}\mathbf{B}_{\mathrm{A-W}} &= \frac{\mu_0}{4\pi}\oint I\frac{(d\mathbf{l}\cdot\mathbf{R})\mathbf{R}}{R^4} = -\frac{\mu_0}{4\pi}arI\int_{-\infty}^{\infty}dz'\int_0^{2\pi}d\phi\,\frac{\sin\phi(r - a\cos\phi), -a\sin\phi, -z')}{(r^2 - 2ar\cos\phi + a^2 + z'^2)^2} \\ &= \frac{\mu_0}{4\pi}\frac{\pi arI}{2}\int_0^{2\pi}d\phi\,\frac{(\sin\phi(r - a\cos\phi), a\sin^2\phi, 0)}{(r^2 - 2ar\cos\phi + a^2)^{3/2}}\,,\end{aligned} \tag{36}$$

using Dwight 120.2 [31]. This is a nonzero function for any value of the distance x of the observer from the axis of the infinite solenoid. The x-component of the final integral is zero, leaving only the y-component, which is also in the $\hat{\boldsymbol{\phi}}$-direction at the observer. The character of $\mathbf{B}_{\mathrm{A-W}}$ is in contrast to the Biot-Savart magnetic field which is zero outside the solenoid and constant inside (with value $\mu_0 I\,\hat{\mathbf{z}}$). For $r \gg a$ (outside the solenoid),

$$\mathbf{B}_{\mathrm{A-W}}(r \gg a) \to \frac{\mu_0}{4\pi}\frac{\pi a^2 rI}{4r^3}\,\hat{\boldsymbol{\phi}} = \frac{\mu_0}{4\pi}\frac{\mathbf{m}\times\mathbf{r}}{4r^3}\,, \tag{37}$$

where $\mathbf{r} = (r, 0, 0)$ and $\mathbf{m} = \pi a^2 I\,\hat{\mathbf{z}}$ is the magnetic dipole moment per unit length of the infinite solenoid. That is, the field lines of $\mathbf{B}_{\text{A}-\text{W}}$ for an infinite solenoid are of the same form as those for a magnetic dipole (sec. 2.3.1 above).

2.3.3 Long, Straight Wire (Aug. 21, 2021)

In this section, we consider a wire along the z-axis, carrying current I.

The Ampère-Weber magnetic field (21) at the point $\mathbf{r} = (r, 0, 0)$ is, integrating over current elements $I\,d\mathbf{l}$ at $\mathbf{r}' = (0, 0, z')$,

$$d\mathbf{l} = (0, 0, dz'), \qquad \mathbf{R} = \mathbf{r} - \mathbf{r}' = (r, 0, -z'), \qquad d\mathbf{l}\cdot\mathbf{R} = -z'\,dz', \qquad R = \sqrt{r^2 + z'^2}, \tag{38}$$

$$\mathbf{B}_{\text{A}-\text{W}} = \frac{\mu_0}{4\pi}\oint I\frac{(d\mathbf{l}\cdot\mathbf{R})\mathbf{R}}{R^4} = -\frac{\mu_0}{4\pi}I\int_{-\infty}^{\infty} dz'\,\frac{z'(r, 0, -z')}{(r^2 + z'^2)^2} = \frac{\mu_0 I}{8r}\,\hat{\mathbf{z}}, \tag{39}$$

using Dwight 122.2 [31]. That is, $\mathbf{B}_{\text{A}-\text{W}}$ is parallel to the wire and falls off inversely with the distance from it.

This result contrasts with Faraday's vision that the lines of magnetic field circle about long, straight, current-carrying wires (Art. 233 of [9]; see also sec. A.17.4 of [48]).

A Appendix: Force Law for a Moving Charge

(Jan. 3, 2023)

We could try to generalize the Ampère-Weber force law, eq. (23), to the case of an electric charge q with velocity $\mathbf{v}$ at position $\mathbf{x}$. Replacing $I_1\,d\mathbf{l}_1$ by $q\,\mathbf{v}$, we infer from eqs. (21)-(23) that,

$$\begin{aligned}\mathbf{F}_{\text{A}-\text{W}}(\mathbf{x}) &= -q\,\mathbf{v}\cdot\int\hat{\mathbf{r}}\,[d\mathbf{B}_{\text{A}-\text{W}}(\mathbf{x},\mathbf{x}') + 2\boldsymbol{\nabla}(d\mathbf{B}_{\text{A}-\text{W}}(\mathbf{x},\mathbf{x}')\cdot\mathbf{r})]\;d\mathbf{Vol}' \\ &= -q\,\mathbf{v}\cdot\frac{\mu_0}{4\pi}\int\hat{\mathbf{r}}\left(\frac{\mathbf{J}(\mathbf{x}')\cdot\hat{\mathbf{r}}}{r^2} + 2\hat{\mathbf{r}}\cdot\boldsymbol{\nabla}\frac{\mathbf{J}(\mathbf{x}')\cdot\mathbf{r}}{r^2}\right)d\mathbf{Vol}',\end{aligned} \tag{40}$$

where $\mathbf{r} = \mathbf{x} - \mathbf{x}'$ is the distance vector from the source point $\mathbf{x}'$ to the observation point $\mathbf{x}$. Recalling eq. (24), this can we written as,

$$\mathbf{F}_{\text{A}-\text{W}}(\mathbf{x}) = \frac{\mu_0}{4\pi}q\int\hat{\mathbf{r}}\frac{3(\mathbf{J}(\mathbf{x}')\cdot\hat{\mathbf{r}})(\mathbf{v}\cdot\hat{\mathbf{r}}) - 2\mathbf{v}\cdot\mathbf{J}(\mathbf{x}')}{r^2}\,d\mathbf{Vol}', \tag{41}$$

which is not a simple function of $\mathbf{B}_{\text{A}-\text{W}}(\mathbf{x})$. Further, $\mathbf{F}_{\text{A}-\text{W}}$ does not equal the Lorentz force,

$$\mathbf{F} = q\,\mathbf{v}\times\mathbf{B} \approx q\,\mathbf{v}\times\frac{\boldsymbol{\mu_0}}{\boldsymbol{4\pi}}\int\frac{\mathbf{J}(\mathbf{x}')\times\hat{\mathbf{r}}}{r^2}\,d\text{Vol}' = \frac{\boldsymbol{\mu_0}}{\boldsymbol{4\pi}}q\int\frac{(\mathbf{v}\cdot\hat{\mathbf{r}})\,\mathbf{J}(\mathbf{x}') - (\mathbf{v}\cdot\mathbf{J}(\mathbf{x}'))\,\hat{\mathbf{r}}}{r^2}\,d\text{Vol}', \tag{42}$$

where the approximation holds for low velocities. This reinforces that the Ampère-Weber magnetic field, $\mathbf{B}_{\text{A}-\text{W}}$, does not have great physical significance.[22]

[22]The Ampère-Weber force law (23) is equivalent to Ampère's original force law (1), which also does not well generalize to an expression for the force on a moving electric charge, or on an isolated current element. Ampère understood this, and inferred that (electrically neutral) isolated current elements could not exist.

B Appendix: Force on a Magnetic Pole (Aug. 21, 2021)

An important insight of Ampère was that all magnetism is due to electric currents, rather than to magnetic poles as had been assumed by all previous workers. In particular (as mentioned in footnote 8 above), Biot and Savart studied the interaction of a magnetic needle with an electric current, supposing that a magnetic pole p resided on the tip of the needle, such that the force law they proposed can be written in vector form as,

$$\mathbf{F} = p\,\mathbf{B}_{\rm B-S}, \qquad \text{where} \qquad \mathbf{B}_{\rm B-S} = \frac{\mu_0}{4\pi}\oint \frac{I\,d\mathbf{l}\times\hat{\mathbf{r}}}{r^2}\,. \tag{43}$$

In particular, for the case of steady current $I\,\hat{\mathbf{z}}$ in a long straight wire, the Biot-Savart magnetic field is $\mathbf{B}_{\rm B-S} = \mu_0 I\,\hat{\mathbf{z}}\times\hat{\mathbf{r}}/2\pi r$ at the magnetic pole p at (transverse) distance $\mathbf{r}$ from the wire.

If we consider that an alternative magnetic field must also describe the force on a magnetic pole according to $\mathbf{F} = p\,\mathbf{B}_{\rm alt}$, then it is clear that the form $\mathbf{B}_{\rm A-W}$ of eq. (21) does not satisfy this. In particular, for the case of the magnetic field (39) due to the current in a long, straight wire (as in the experiment of Biot and Savart [1]), $\mathbf{B}_{\rm A-W} = \mu_0 I\,\hat{\mathbf{z}}/16r$ is parallel to the wire, which would imply a force on the pole parallel to the wire, rather than in the direction $\mathbf{I}\times\mathbf{r}$ as observed experimentally.

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